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NASA Technical Memorandum 106462

The Tribology of PS212 Coatings and PM212 Composites for the Lubrication of Titanium 6A1–4V Components of a Stirling Engine Space Power System

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Prepared for the
Annual Meeting
sponsored by the Society of Tribologists and Lubrication Engineers
Pittsburgh, Pennsylvannia, May 2–5, 1994

National Aeronautics and
Space Administration

THE TRIBOLOGY OF PS212 COATINGS AND PM212 COMPOSITES FOR THE LUBRICATION OF TITANIUM 6Al–4V COMPONENTS OF A STIRLING ENGINE SPACE POWER SYSTEM

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ABSTRACT

The Stirling space power machine incorporates a linear alternator to generate electrical power. The alternator is a reciprocating device that is driven by a solar or nuclear-powered Stirling engine. The power piston and cylinder are made of titanium 6Al–4V (Ti6–4) alloy, and are designed to be lubricated by a hydrodynamically-generated gas film. Rubbing occurs during starts and stops and there is the possibility of an occasional high speed rub. Since titanium is known to have a severe galling tendency in sliding contacts, a "back-up," self-lubricating coating on the cylinder and/or the piston is needed. This report describes the results of a research program to study the lubrication of Ti6–4 with the following chromium carbide based materials: plasma-sprayed PS212 coatings and sintered PM212 counterfaces. Program objectives are to achieve adherent coatings on Ti6–4 and to measure the friction and wear characteristics of the following sliding combinations under conditions simulative of the Stirling-driven space power linear alternator: Ti6–4/Ti6–4 baseline, Ti6–4/PS212-coated Ti6–4, and PS212-coated Ti6–4/PM212.

INTRODUCTION

A linear alternator, which is driven by a Stirling cycle engine, is under consideration by NASA for the generation of electrical power in space (1,2). One side of a two cylinder, linearly opposed space power Stirling engine is shown in Fig. 1(a). A more detailed drawing of the linear alternator is shown in Fig. 1(b). Magnets attached to the power piston cut magnetic lines of force in a reciprocating linear motion in contrast to the rotary motion employed in a conventional electrical alternator.

The power piston and cylinder are made of titanium 6Al–4V (Ti6Al–4V) alloy. This material was chosen because of its light weight and high strength. Unfortunately, titanium and its alloys have poor tribological properties, especially in regard to their tendency to scuff and gall when in sliding contact with themselves or many other alloys. In the current design, the piston is a free piston that spins in the cylinder and functions as a gas bearing. The piston/cylinder clearance is very small, on the order of 10 μm. Under ideal steady state conditions, a hydrodynamically pressurized gas film prevents contact between the piston and cylinder. However, contact occurs during starts and stops and occasional high speed rubs may occur. This necessitates the use of a back-up self-lubricating coating to prevent scuffing, galling and possibly catastrophic seizure of the piston and cylinder in the event of a scuff. This is especially important because of the severe galling tendency of uncoated titanium.

In this study, PS212, a plasma sprayed, self-lubricating composite coating is investigated as a lubricant for Ti6–4. This coating and its powder metallurgy modification, sintered PM212, are composites of metal-bonded chromium carbide, silver, and barium fluoride-calcium fluoride eutectic. For detailed information on these materials, see refs.3 to 11. The program goals were to develop adherent PS212 coatings on Ti6–4 alloy and to evaluate friction and wear under conditions similar to those in the linear alternator of the Stirling space power machine.The sliding combinations evaluated were: (1) Ti6–4 on itself for baseline data; (2) Ti6–4 on PS212-coated Ti6–4; (3) sintered PM212 on Ti6–4; and (4) sintered PM212 on PS212-coated Ti6–4. Since PM212 is of the same chemical composition as PS212, sliding combination (4) is here considered equivalent to PS212 sliding on itself.

MATERIALS

The chemical composition of Ti6–4 is given in Table I from (12). The nominal composition of PS212 or PM212 by weight per cent is 70 nickel alloy bonded chromium carbide (Cr_3C_2),15 silver, and 15 barium fluoride-calcium fluoride eutectic. The corresponding volume per cents of the components are given in Table II (13). For quality control purposes, the acceptable weight percentage ranges by chemical elements are given in Table III (13).

The microstructure of a diamond ground PS212 coating is shown in Fig. 2(a). The dark areas are nickel alloy-bonded chromium carbide; the light areas are pockets of fluoride eutectic and of silver. The component distribution throughout the coating thickness is seen in Fig. 2(b) which is a back-scattered SEM image of a polished cross section of the coating. The components are called out on the picture. Note the highly stratified structure which is typical of plasma sprayed coatings.

Optical photomicrographs of sintered PM212 are shown in Figs. 3(a) and (b). With vertical illumination, the dark areas appear to be porosity. However, with oblique illumination, contrast is reversed, and the most of the areas that appeared to be porosity, are now clearly seen to be the pockets of translucent fluorides. Component distribution is random compared to the stratified structure of the coatings.

SEM back scatter images of PM212 are shown in Figs. 4(a) and (b). Porosity and the various components of the composite are now all discernable. Note the lamellar structure of the fluoride eutectic with alternate bands of barium fluoride and calcium fluoride.

MATERIAL PREPARATION

Detailed description have been given elsewhere for the preparation of PS212 coatings (13), and for sintered PM212 (6). Therefore only brief descriptions will be given here.

Powder Preparation

Powder preparation is the same for PS212 or PM212. The two fluoride powders are blended together in eutectic proportions. They are then melted in a graphite crucible in a dry nitrogen atmosphere at 1100 °C. The melt is held at this temperature for 1 hour, then cooled to room temperature. The solidified eutectic is then removed from the crucible, crushed, ball milled, and sieved to obtain a particle size range of 44 to 77 μm. The eutectic powder is then blended with the carbide and silver powders in a Vee blender. The powders are then processed into plasma sprayed coatings or into powder metallurgy parts. The plasma sprayed coatings are applied to an intermediate thin coating of nichrome on Ti6–4. The bond coat is 0.08 mm thick, and the PS212 top coat is 0.18 mm thick after finish grinding. Preparation of PM parts is briefly described in the following:

PM212 Preparation

A green compact of the blended powders is compacted either by cold die pressing or, as in the present case, by cold isostatic pressing (CIP). The powder is first poured into a rubber mold which is then evacuated with a vacuum pump. The mold is sealed, placed in an aluminum support container, then immersed in a liquid pressure chamber. The powders are compacted isostatically at high pressure. The cold pressed compact is then removed from the mold and sintered in dry hydrogen at 1100 °C. Very dry hydrogen must be used to prevent the formation of chromium oxide during sintering.

Finishing

Some shapes of PM212 can be cold die pressed into near final dimensions. CIPed PM212 can only be compacted to approximate dimensions because the rubber mold cannot produce accurate dimensions. In any case, some finishing operation is required to produce the desired dimensions and surface finish. Blank forms are rough machined with carbide-tipped tools or by EDM. Final finishing, especially of bearing surfaces is by diamond or cubic boron nitride (CBN) grinding. PS212 coatings are finish ground in the same way.

TEST PROCEDURE

A drawing of the pin on disk tribometer used in this study is shown in Fig. 5. The disk specimen is induction-heated, and the surface temperature is continuously measured with an infrared pyrometer. The pin is fixed and generates a 51-mm diameter wear track on the rotating disk. The tip of the wear pin is hemispherical with a radius of 4.76 mm.

Friction and wear experiments are conducted under conditions as simulative of the linear alternator application as possible in a simple pin-on-disk test with unidirectional rotation. The tests are run in dry nitrogen which is the atmosphere to be used in laboratory tests of the linear alternator. Sliding conditions are: 4 m/s, which is the root mean square average of the piston velocity, 4.9 N normal load, and temperatures of 25 °C (baseline) and 125 °C, the estimated temperature in the vicinity of the power piston.

Pin and disk wear volumes are determined after each test. Briefly, pin wear is determined by using a microscope to measure the diameter of the circular wear scar worn on the hemispherical tip of the pin, then computing the corresponding wear volume as described in (14).

Disk wear volume is determined as follows: A stylus profilometer is used to trace and to compute the cross sectional area of the wear track. The cross sectional area is measured in three to four positions of the wear track circumference, the average of these is multiplied by the circumference of the circular wear track to give the volumetric wear.

Wear data are presented in this paper as volumetric wear factors. The wear factors are calculated by dividing the volumetric wear by the normal load and the sliding distance. The units are:

$$k = \mathrm{mm^3/Nm}$$

Four tests were performed at 25 and 125 °C for each of the combinations Ti6–4/Ti6–4 and PM212/Ti6–4. Two tests at each temperature were performed for the combinations Ti6–4/PS212 and PM212/PS212 for a total of 24 tribotests in this program.

EXPERIMENTAL RESULTS

Since the power piston and the cylinder of the Space Power Stirling are both made of Ti6–4, baseline friction and wear behavior of Ti6–4 pins sliding on Ti6–4 disks was measured for comparison with Ti6–4 sliding on PS212, PM212 sliding on Ti6–4, and finally PM212 sliding on PS212-coated Ti6–4. The quantitative results are presented graphically in Figs. 6 and 7 and are summarized in Table IV. The data clearly indicate that the titanium alloy sliding against itself or against either PS212 or PM212 results in relatively high friction and wear. Much improved results are observed for PM212 pins sliding against PS212-coatings on Ti6–4 disks.

Friction coefficients (Fig. 6) for the Ti6–4 against Ti6–4, PM212, or PS212 are typically in the range of 0.36 to 0.45. On the other hand, the friction coefficients for PM212 versus PS212-coated Ti6–4 are 0.13 to 0.19 at 25 °C and 0.18 to 0.22 at 125 °C.

Wear factors are given in Figs. 7(a) and (b). Wear factors for PM212 pins sliding against PS212 are about 1/1000th the magnitudes for the other material combinations at 25 °C and 1/1000th to 1/100th the magnitude of the other material combinations at 125 °C.

Surface profiles across representative wear tracks are shown in Figs. 8(a) and (b) for tests at 25 °C and in Figs. 9(a) and (b) for tests at 125 °C. Deeply worn wear tracks are evident on the uncoated Ti6–4 disks, while the wear depths on PS212-coated Ti6–4 after sliding against PM212 pins are not measurable above the background profile of the coating outside of the wear area.

Photomicrographs, all at the same magnification, of the corresponding pin wear scars and disk wear track segments are shown in Figs. 8(c) and (d) and 9(c) and (d). Pin wear scars on the Ti6–4 pins are seen to be huge compared to the small wear scars on the PM212 pins that had been slid against PS212-coated Ti6–4. Wide wear tracks, and evidence of severe adhesive wear are evident on the uncoated Ti6–4 disks. In contrast, wear areas are barely distinguishable on the PS212 coatings. The combination of a thin bond coat of nickel-chromium with a top coat of PS 212 is an adherent coating system for Ti6–. No chipping or spalling of the PS212 coatings was observed on any of the disk specimens after either finish grinding or friction and wear testing.

CONCLUSIONS

1. The results of this tribotest program demonstrate the poor tribological properties, especially the severe wear characteristics of titanium 6Al–4V.

2. High friction and wear occurred in baseline tests of Ti6–4 versus Ti6–4. No improvement was observed for Ti6–4 sliding against PS212 or PM212. The wear mode was severe adhesive wear accompanied by galling.

3. Ti6–4 transfers during wear to the surface of the counterface so that, in a short time, the sliding surfaces are Ti6–4 versus a layer of transferred Ti6–4 adhering to the counterface material.

4. PM212 sliding against PS212-coated Ti6–4 gave low friction and wear at 25 and 125 °C in a dry nitrogen atmosphere.

5. The plasma-sprayed PS212 coatings, with a thin, intermediate bond coat of nichrome, adhered strongly to the Ti6–4 substrates.

REFERENCES

1. Alger, D.L.: "Progress Toward the Evolution of a Stirling Space Engine," SAE Technical Paper, 880545, 1988.

2. Cairelli, J.E.; and Geng, S.M.: "Results from Baseline Tests of the SPRE I and Comparison with Code Model Predictions," NASA TM–102044, 1989.

3. Sliney, H.E.: U.S. Patent 4,728,488: Carbide/Fluoride/Silver Self-Lubricating Composites, issued Mar. 1, 1988.

4. Sliney, H.E.; and DellaCorte, C.: U.S. Patent 5,034,187: Method of Making Carbide/ Fluoride/Silver Composites, issued July 23, 1991.

5. DellaCorte, C.; and Sliney, H.E.: "Composition Optimization of Self-Lubricating Chromium Carbide-Based Composite Coatings for Use to 760 °C," ASLE Trans., vol. 30, no. 1, Jan. 1987, pp. 77–83.

6. DellaCorte, C.; and Sliney, H.E.: "Tribological Properties of PM212: A High Temperature, Self-Lubricating, Powder Metallurgy Composite," Lubr. Eng., vol. 47, no. 4, Apr. 1991.

7. Edwards, P.M., et al.: "Mechanical Strength and Thermophysical Properties of PM212: A High Temperature, Self-Lubricating Powder Metallurgy Composite," NASA TM–103694, DOE/NASA/50162–5, 1990.

8. Sliney, H.E.: "A New Chromium Carbide-Based Tribological Coating for Use at 900 °C with Particular Reference to the Stirling Engine," J. Vac. Sci. Technol. A, vol. 4, no. 6, Nov./Dec. 1986, pp. 2629–2632.

9. Sliney, H.E.: "Coatings for High Temperature Bearings and Seald," NASA TM–100249, DOE/NASA/50112–71, 1987.

10. Sliney, Harold E.: Some Composite Bearing and Seal Materials for Gas Turbine Applications—A Review," J. Eng. Gas Turbines Power, vol. 112, no. 4, Oct. 1990, pp. 486–491.

11. Sliney, H.E.: "Composite Bearing and Seal Materials for Advanced Heat Engine Applications to 900 °C, NASA TM–103612, DOE/NASA 50162–4, 1990.

12. Anonymous author, Titanium Metals Corporation of America: "Properties of Ti–6Al–4V," Timet Titanium Engineering Bulletin, no. 1.

13. Sliney, H.E.; and DellaCorte, C.: "Quality Control of the Tribological Coating—PS212," NASA TM–102067, June 1989.

TABLE I.—CHEMICAL COMPOSITION OF Ti–6Al–4V

Element	Sheet, strip, plate, and wire weight, percent	Bar, billet, tubing, and extrusions weight, percent
Aluminum	5.5-6.5	5.75-6.75
Vanadium	3.5-4.5	3.5-4.5
Iron	0.25 maximum	0.25 maximum
Carbon	0.08 maximum	0.08 maximum
Nitrogen	0.05 maximum	0.05 maximum
Hydrogen	0.015 maximum	0.0125 maximum
Oxygen[a]	0.20 maximum	0.20 maximum

[a]The maximum oxygen content of the Ti–6Al–4V ELI grade is 0.13 percent.

TABLE II.—COATING COMPOSITION GUIDE

(a) Allowable composition scatter in PS212 coating components

Component	Scatter, wt %
Metal-bonded Cr_3C_2	70±6
Ag	15±3
BaF_2/CaF_2 eutectic (62/38 weight ratio)	15±3

(b) Elemental Compositions of coatings

Element[a]	Nominal composition of metal-bonded Cr_3C_2, wt %	Composition range for PS212, wt %	Elements analyzed by EDS or XRF
Cr	48	33.6±3.0	X
C	6	4.2 (nominal)	(b)
Ni	28	19.6±2.0	X
Co	12	8.4±0.8	X
Al	2	1.4±0.2	X
Ag	0	15.0±3.0	X
Ba		7.3±1.5	X
Ca		2.9±0.6	X
F		4.8±1.0	(c)

[a]Balance: Mo, B, and Si.
[b]Not analyzed. Computed as 70 percent of carbon in metal-bonded chromium carbide.
[c]Not analyzed. Computed from analyses for Ba and Ca.

TABLE III.—NOMINAL VOLUMETRIC COMPOSITION OF PS212

[Theoretical average density: $\bar{\sigma}$ = 6.60 gms/cm^3.]

Component	Density, gm/cm^3	Content in PS212, vol %
Cr_3C_2	6.68	37.2
Ni alloy binder	-------	Balance
Ag	10.50	9.4
BaF_2	4.80	11.8
CaF_2	3.18	12.7

TABLE IV.—TRIBO-DATA FOR EACH TEST IN THIS PROGRAM

[Test conditions: air atmosphere 2.9N load 4-m/sec velocity 60-min duration.]

Specimens		Test temperature, °C	Wear factors, mm^3/Nm		Friction coefficient
Pin	Disk		K(pin)	K(disk)	
Ti6–4	Ti6–4	25	8.5×10^{-5}	9.1×10^{-5}	0.36±0.02
			6.1	15.9	0.36±0.01
			8.3	23.1	0.36±0.02
			6.8	19.2	0.35±0.01
		125	8.5×10^{-5}	19.1×10^{-5}	0.40±0.02
			6.3	15.0	0.36±0.01
			8.5	26.9	0.40±0.02
			71.5	23.5	0.38±0.01
Ti6–4	PS212	25	12.6×10^{-5}	25.8×10^{-5}	0.43±0.04
			17.0	22.4	0.46±0.04
		125	1.42×10^{-5}	4.0×10^{-5}	0.36±0.06
			0.74	2.7	0.38±0.02
PM212	Ti6–4	25	8.8×10^{-5}	6.3×10^{-5}	0.43±0.02
			6.2	1.3	0.44±0.01
			8.0	7.7	0.45±0.03
			6.1	4.4	0.45±0.02
		125	5.0×10^{-5}	7.0×10^{-5}	0.49±0.05
			5.3	3.6	0.51±0.02
			10.3	11.3	0.46±0.03
			8.7	12.2	0.47±0.01
PM212	PS212	25	3.6×10^{-8}	Below detection limit	0.14±0.01
			7.4		0.17±0.02
		125	1.8×10^{-7}	Below detection limit	0.20±0.02
			1.3		0.19±0.01

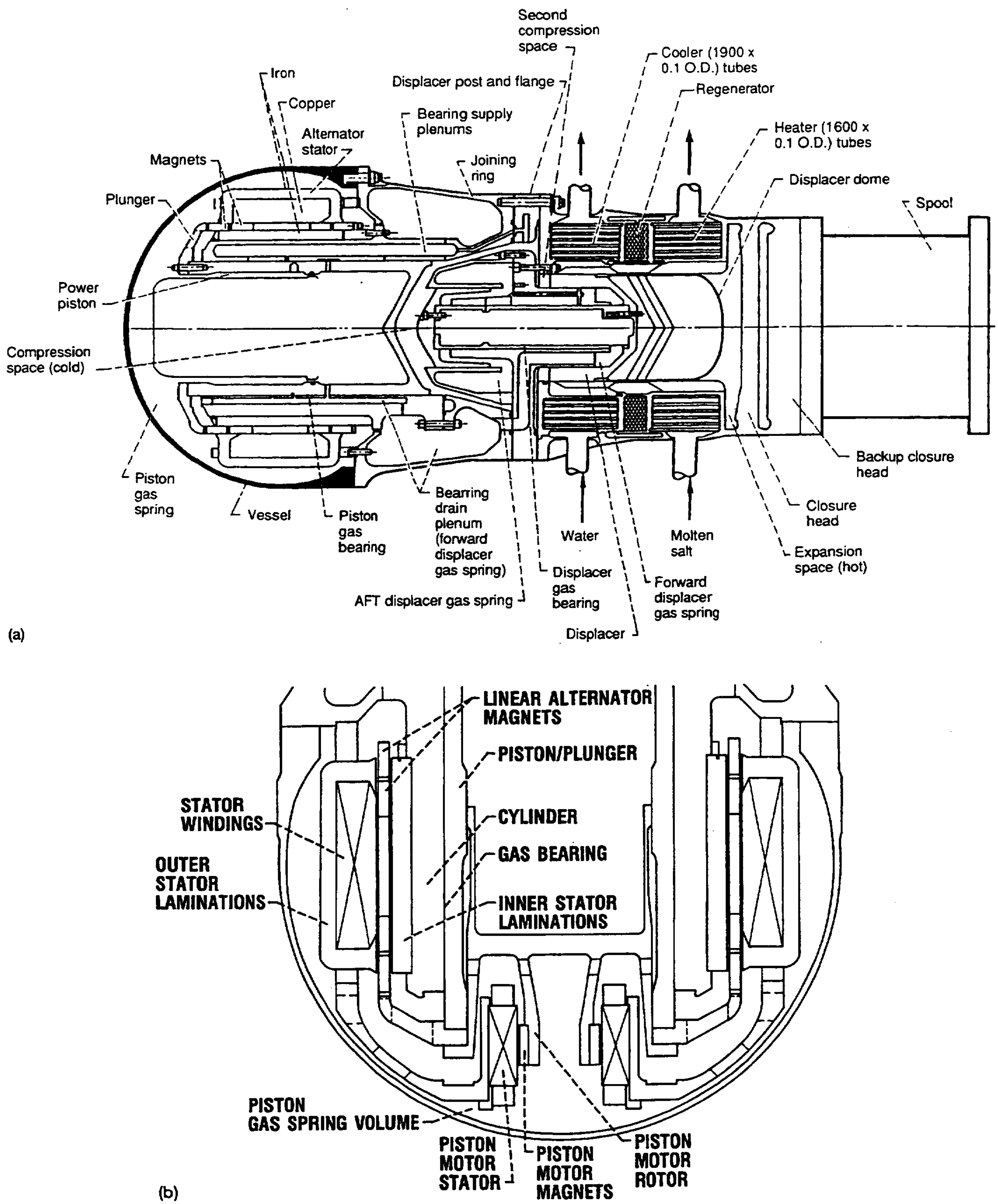


Figure 1.—Space Power Sterling Engine. (a) Engine cross section. (b) Linear alternator detail.

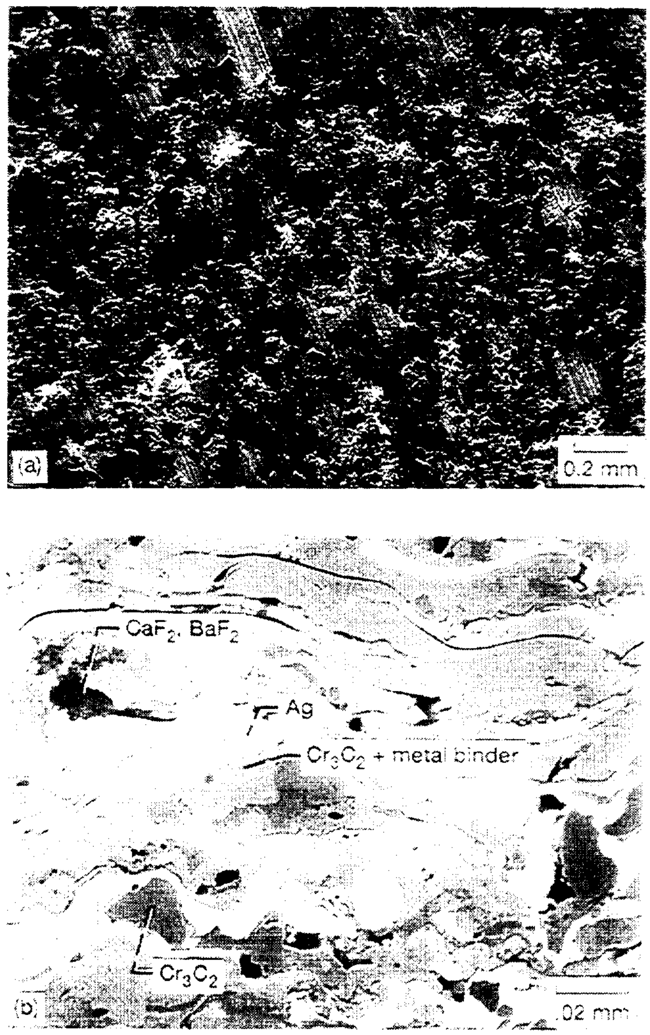


Figure 2.—Microstructure of PS212 by SEM. (a) Diamond ground PS212 original magnification of 50x. (b) Cross section of PS212 showing distribution of components original magnification of 600x.

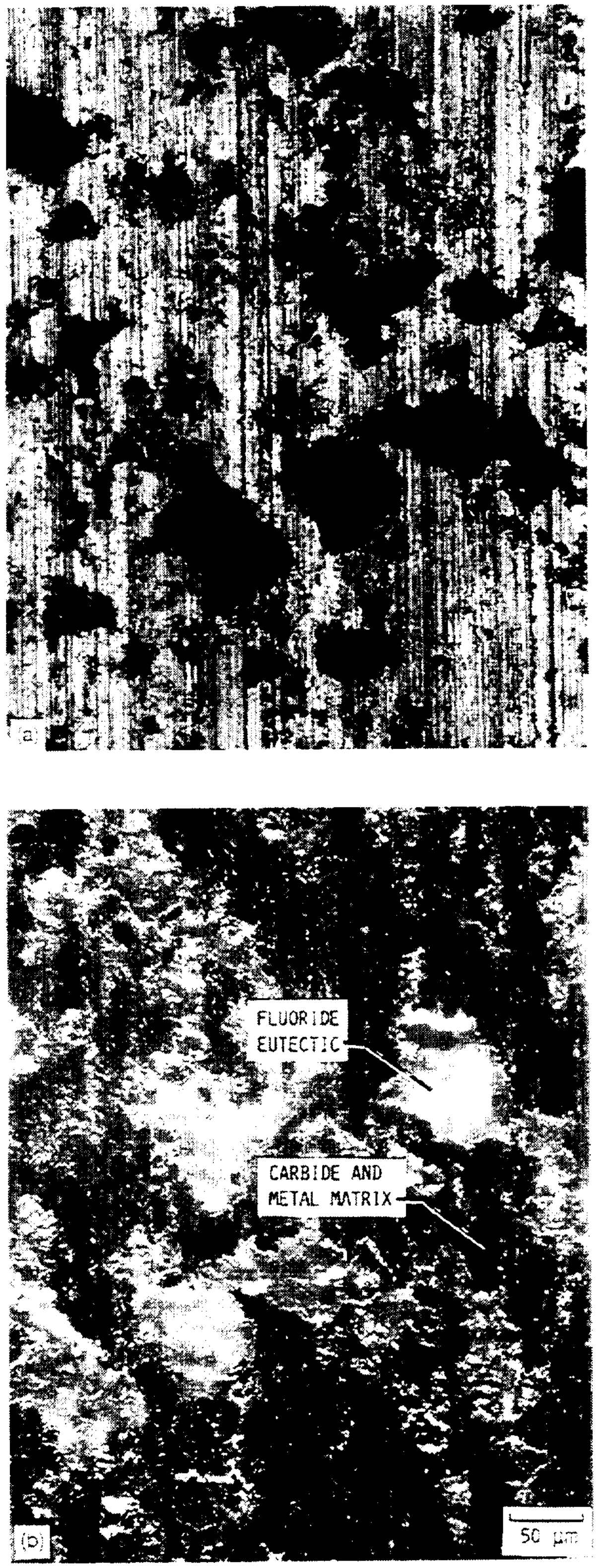


Figure 3.—PM212 microstructure by optical microscopy. (a) Vertical illumination. (b) Oblique illumination.

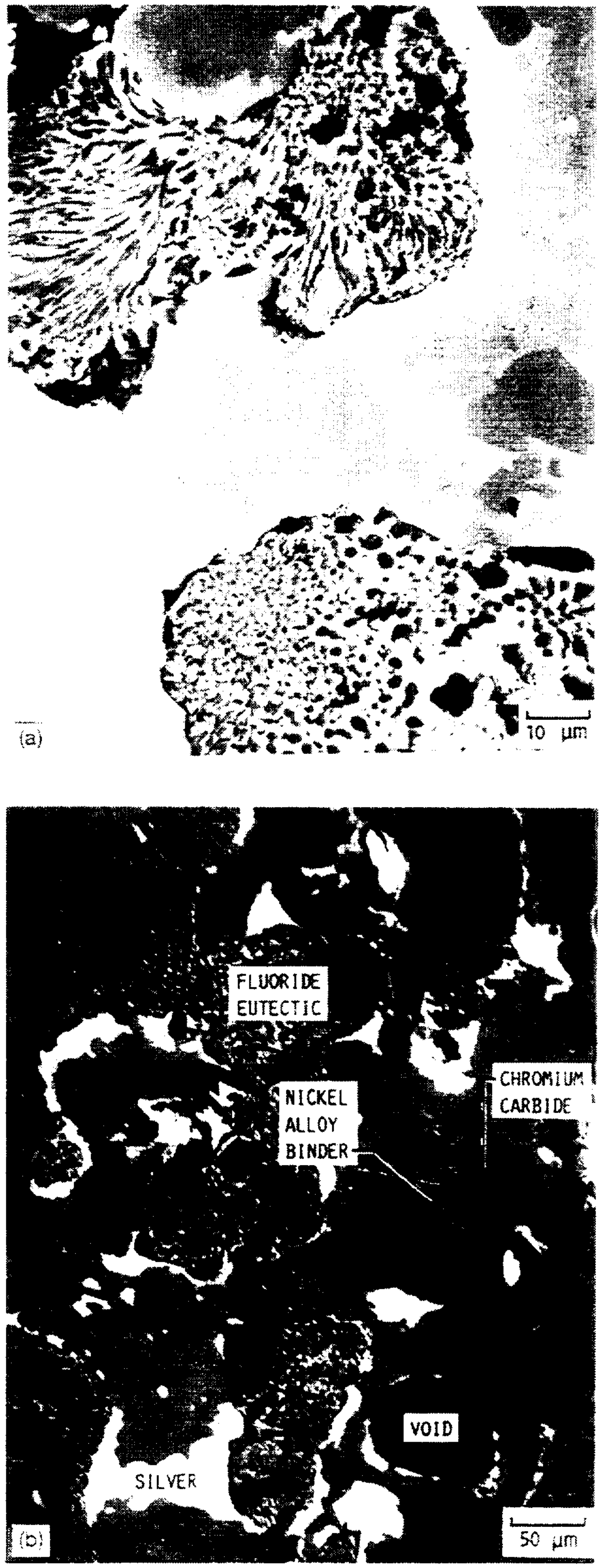


Figure 4.—Distribution of components in sintered PM212 by back scatter mode of SEM. (a) Eutectic detail. (b) Component identification.

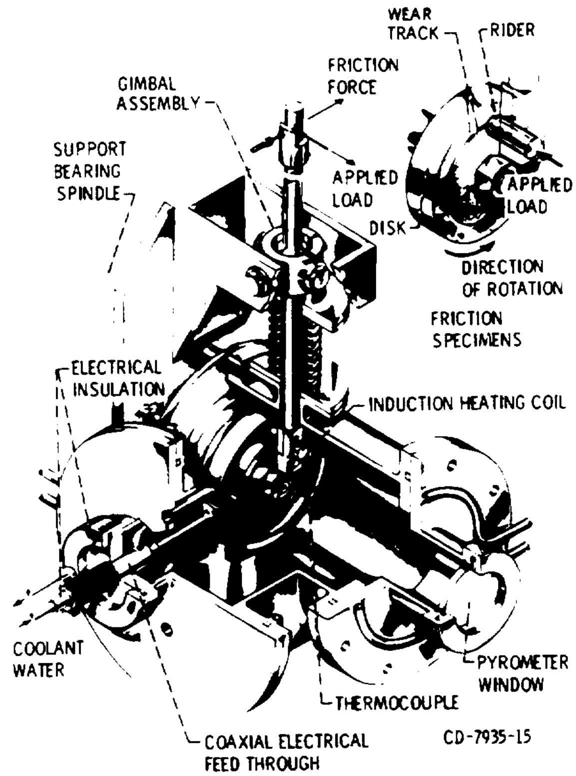


Figure 5.—Induction heated pin-on-disk rig.

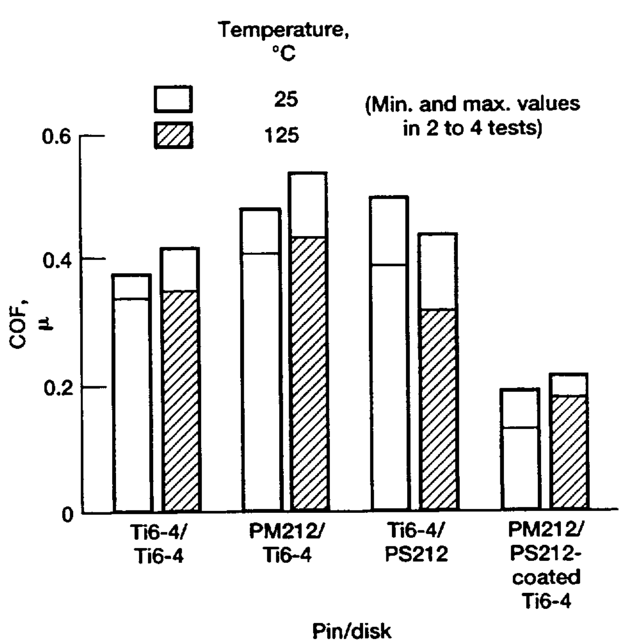


Figure 6.—Friction of sliding material pairs, nitrogen atmosphere, 2.94-N load, 4.76-mm initial pin radius, 1550-rpm speed, 4.7-m/s sliding velocity.

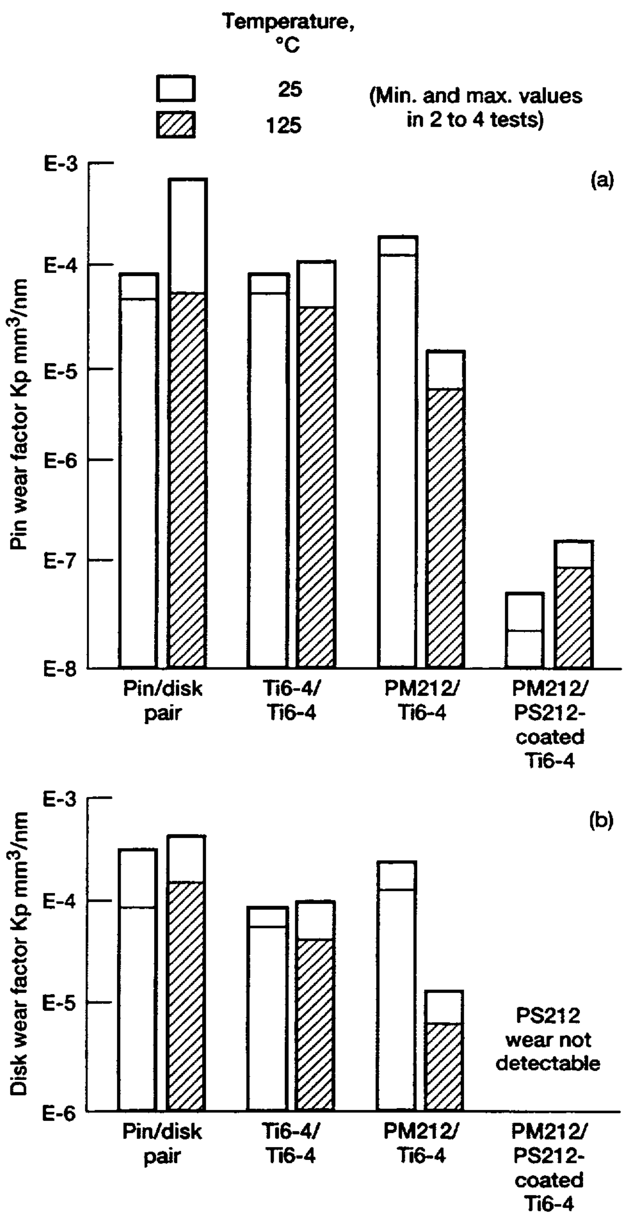
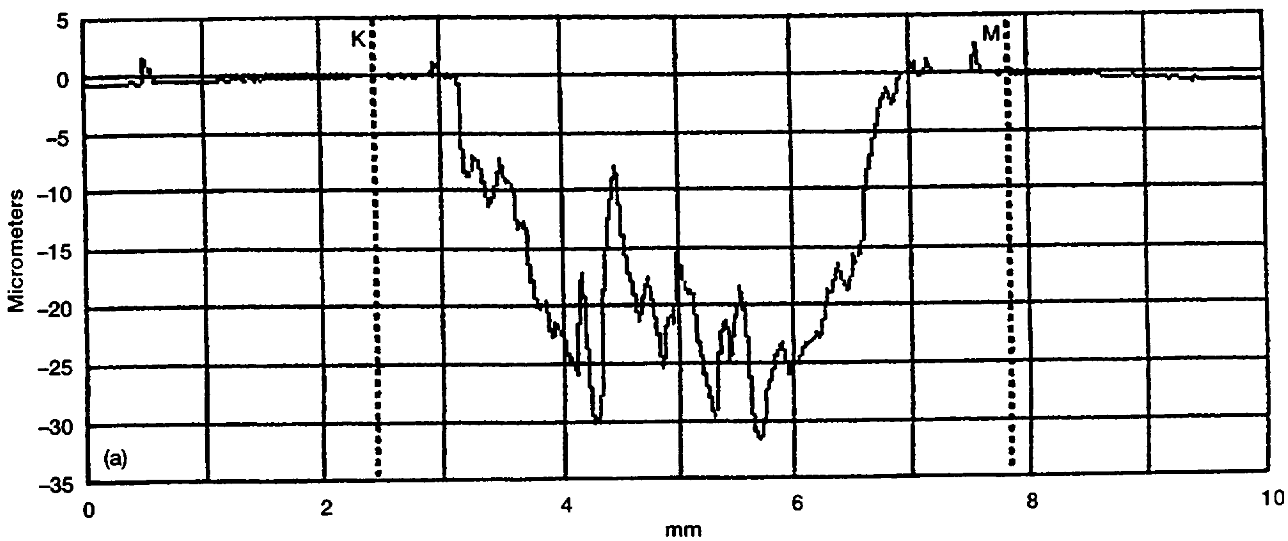


Figure 7.—Wear factors for various pin on disk material pairs. Test conditions: nitrogen atmosphere, 1-hour duration, 2.94-N load, 4.76-mm pin radius, 1550-rpm speed, 4.7-m/s sliding velocity. (a) Pin wear. (b) Disk wear.



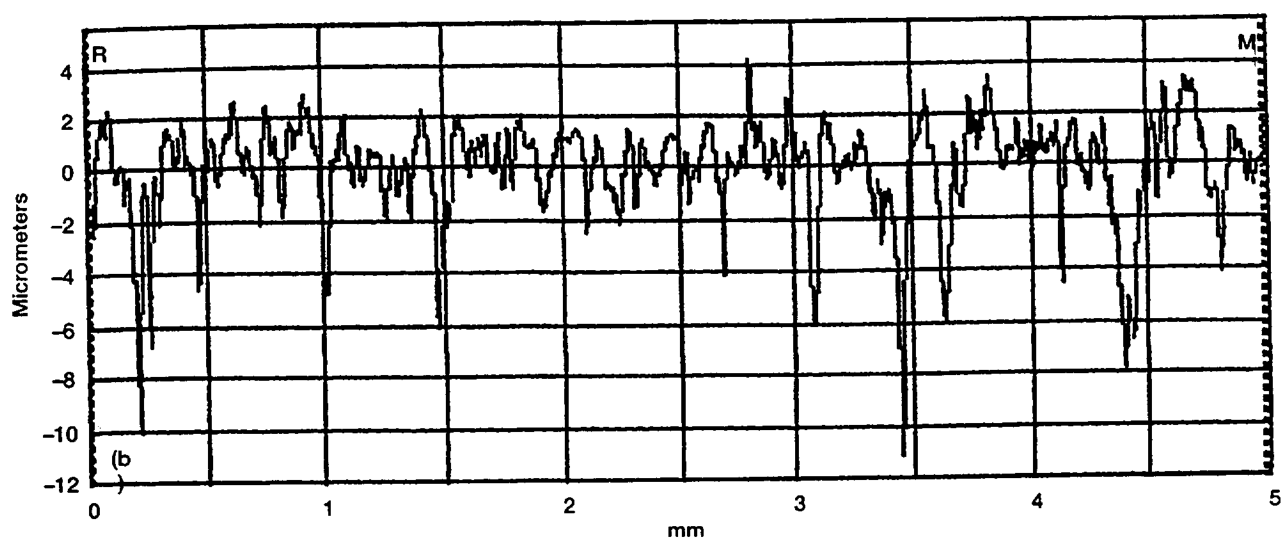


Figure 8.—Comparative wear after tribotests at 25 °C test conditions: nitrogen atmosphere, 1-hour duration, 2.9-N load, 4.76-mm initial pin radius, 1550-rpm speed, 4.7-m/s sliding velocity. (a) Profile across wear track after tribotest of Ti6-4/Ti6-4 at 25 °C. (b) Profile across wear track after tribotest of PM212/PS212-coated Ti6-4.

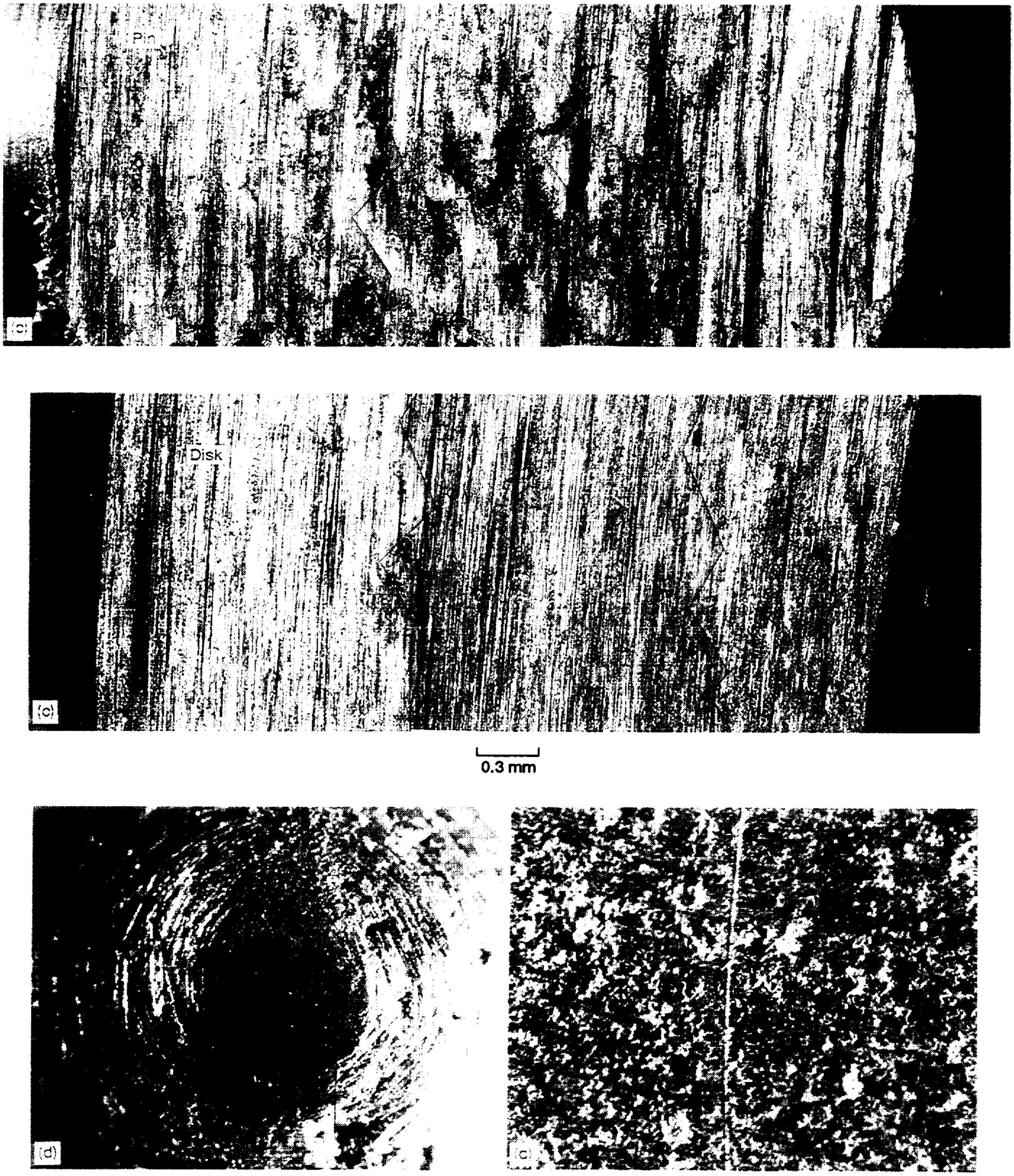


Figure 8.—Concluded. (c) Wear scar segment on Ti6-4 pin; wear track segment on Ti6-4 disk. (d) Wear scar on PM212 pin; wear track segment on PS212-coated Ti6-4 disk.

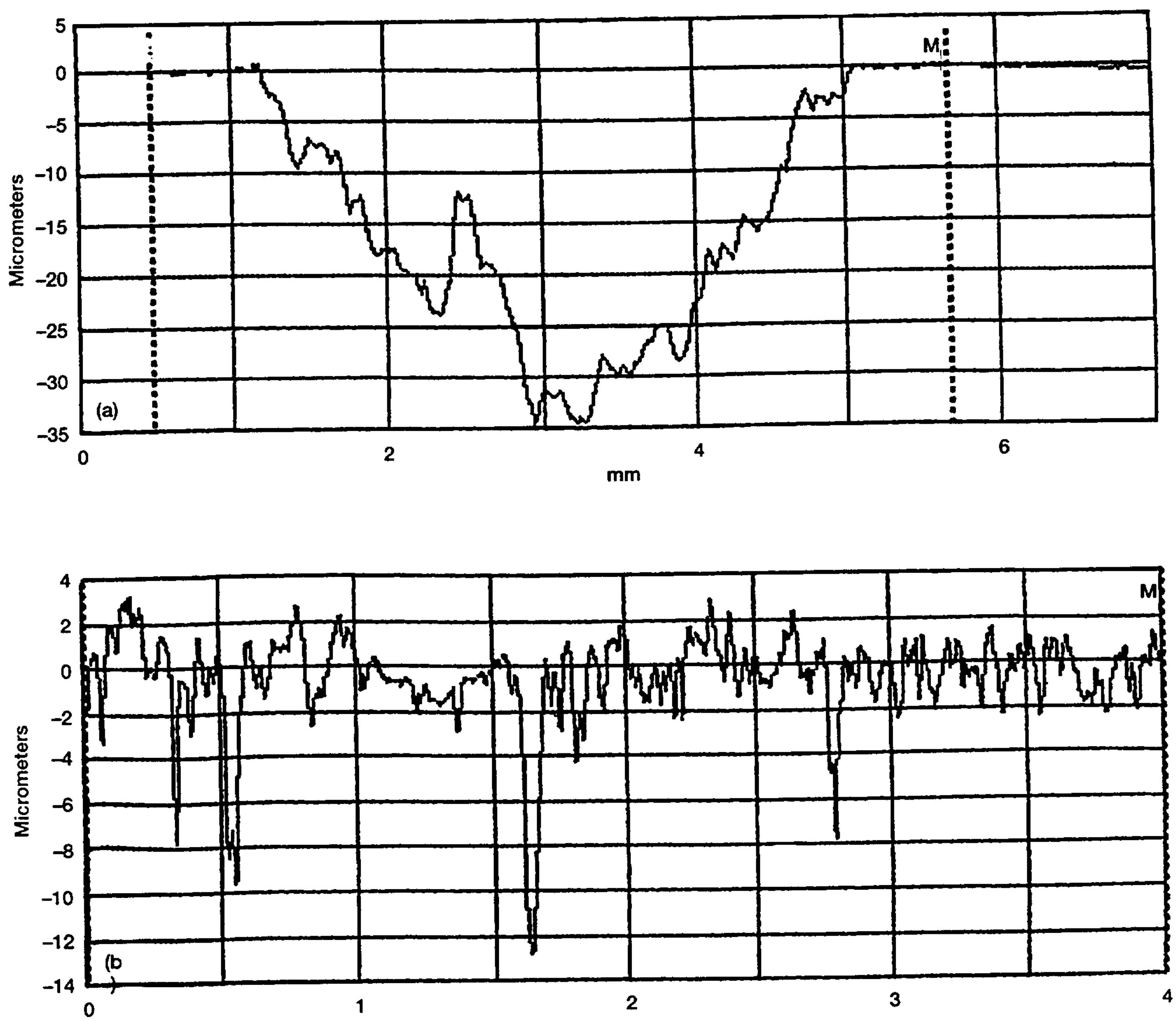


Figure 9.—Comparative wear after tests at 125 °C test conditions: nitrogen atmosphere, 1-hour duration, 2.9-N load, 4.76-mm initial pin radius, 1550-rpm speed, 4.7-m/s sliding velocity. (a) Profile across wear track after tribotest of Ti6-4/Ti6-4 at 125 °C. (b) Profile across wear track after tribotest of PM212/PS212-coated Ti6-4.

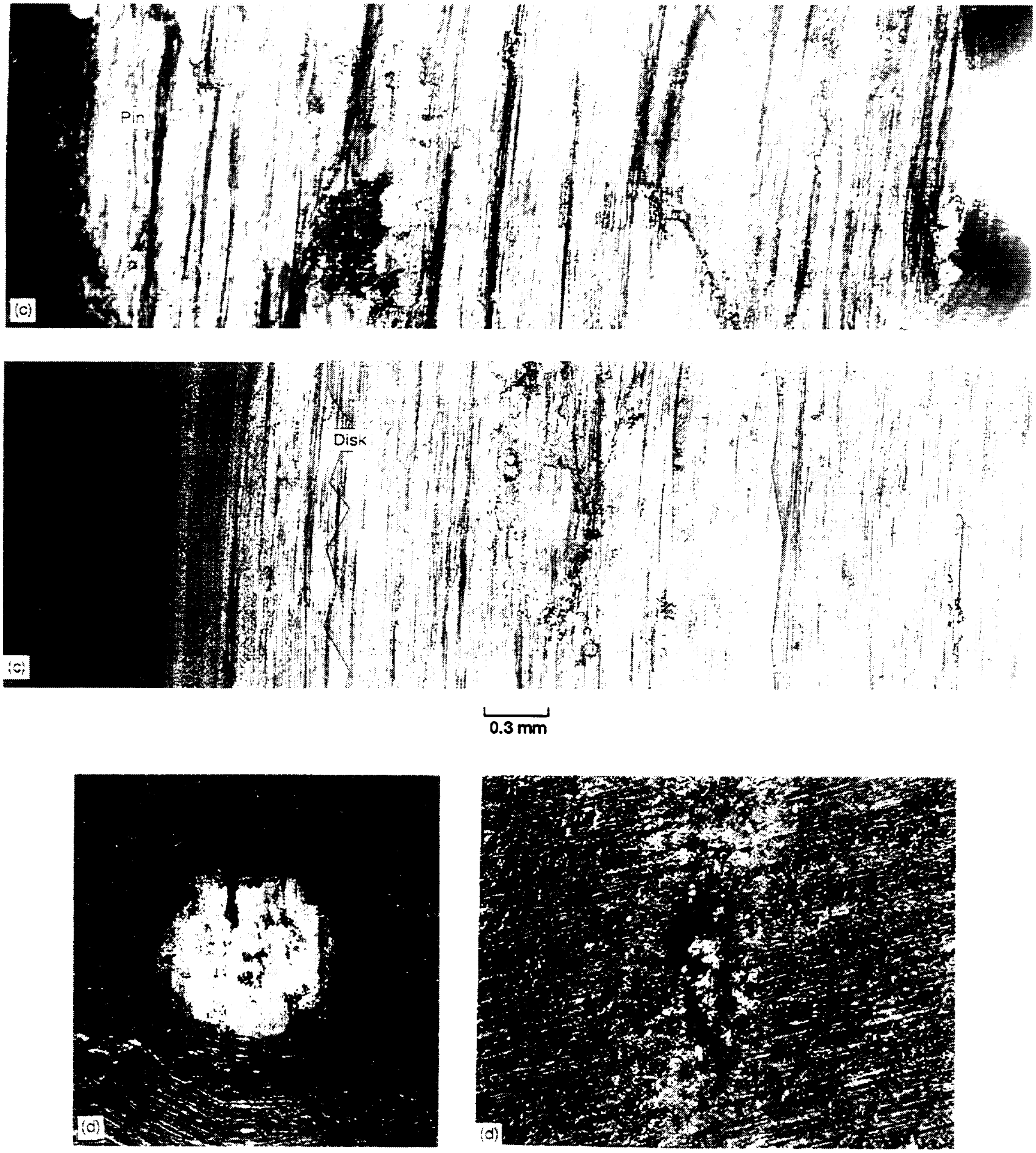


Figure 9.—Concluded. (c) Wear scar segment on Ti6-4 pin; wear track segment on Ti6-4 disk. (d) Wear scar on PM212 pin; wear track segment on PS212-coated Ti6-4 disk.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1994

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
The Tribology of PS212 Coatings and PM212 Composites for the Lubrication of Titanium 6A1–4V Components of a Stirling Engine Space Power System

5. FUNDING NUMBERS
WU–505–63–5A

6. AUTHOR(S)
Harold E. Sliney, Victor Lukaszewicz, and Christopher DellaCorte

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–8325

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–106462

11. SUPPLEMENTARY NOTES
Prepared for the Annual Meeting sponsored by the Society of Tribologists and Lubrication Engineers, Pittsburgh, Pennsylvannia, May 2–5, 1994. Harold E. Sliney and Christopher DellaCorte, NASA Lewis Research Center; Victor Lukaszewicz, Calspan Corp., 21765 Brookpark Road, Fairview Park, Ohio 44126 (work funded by NASA Contract NAS3–25685). Responsible person, Harold E. Sliney, organization code 5140, (216) 433–6055.

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Unclassified - Unlimited
Subject Category 23

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS
Solid lubrication; Titanium; Space power; Stirling

15. NUMBER OF PAGES
20

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102